NRL Report 7990

Development of a Superconducting ELF Receiving Antenna

JOHN R. DAVIS, ROBERT J. DINGER, AND JOSEPH GOLDSTEIN

Electromagnetic Propagation Branch
Communications Sciences Division

April 9, 1976

NAVAL RESEARCH LABORATORY
Washington, D.C.

ERRATUM

NRL Report 7990

An error committed in comparing with noise both the motion-stability spectral data in Fig. 4 and higher frequency data (not pictured) affects certain aspects of the motion-noise reduction discussion on pages 10 through 15. Although all data as presented are accurate, the spectral resolution bandwidth of approximately 0.06 Hz used in processing these data was neglected in comparing them with atmospheric noise on a per-square-root-hertz basis. Consequently, all ratios of motion noise to atmospheric noise and the conclusions based on them are overly optimistic by about 12 dB.

Because of this factor, the actual linear dynamic range requirement is approximately 148 dB, and the in-band motion noise that must be removed by the adaptive signal processing technique is 88 dB above receiver sensitivity.

Neither of these circumstances substantially alters the conclusions. Current technology can provide SQUID systems with this higher required dynamic range, and the signal processing technique advanced for providing the motion-noise compensation was found (cf. p. 13) to have an adequate margin to accommodate this error. An expanded error analysis, to be reported in greater detail in a subsequent report, indicates that the deviations of the sensor axes from orthogonality [0.7×10^{-4} radian maximum] and fractional SQUID electronics sensitivity errors remain adequate for this motion-noise removal.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NRL [redacted]7999 (14)

2. GOVT ACCESSION NO.: -

3. RECIPIENT'S CATALOG NUMBER: (9)

4. TITLE (and Subtitle): DEVELOPMENT OF A SUPERCONDUCTING ELF RECEIVING ANTENNA (6)

5. TYPE OF REPORT & PERIOD COVERED: Interim report, on one phase of a continuing NRL Problem

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): John R. Davis, Robert J. Dinger[redacted] Joseph Goldstein (10)

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Research Laboratory, Washington, D.C. 20375

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: (16) NRL ~~Problem~~ R07-34; [redacted]XF21-222

11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Electronic Systems Command, Washington, D.C. 20375

12. REPORT DATE: (11) (9) Apr[redacted]76

13. NUMBER OF PAGES: 21

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (12) 23p.

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited. (17) XF21-222-035

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Extremely low frequencies
Submarine antennas
Antennas
Receivers
Superconductors

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The development of an ELF submarine receiving antenna that uses a triaxial array of superconducting quantum interference devices (SQUIDs) has addressed the achievement of a SQUID sensor with a sensitivity of 0.01 picotesla per hertz to the 1/2 power, achievement of a SQUID linear dynamic range of 140 dB, achievement of sensor orthogonality of 0.1 milliradian, stabilization of receiver platform motion to 1 milliradian, processing of SQUID outputs to remove residual motion noise, and provision of a suitable cryogenic environment. The required sensitivity, linear dynamic range, and sensor orthogonality were obtained in a prototype point-contact-type
(Continued) over

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

251 750 — 13

20. Abstract (Continued)
triaxial SQUID magnetometer used to detect the ELF signal from the Navy test transmitter in Wisconsin. The required platform stabilization was demonstrated in a towing basin by motion spectrum measurements on a hydrodynamically stabilized buoy designed to be towed by a submarine. Motion excursions within the ELF passband of 30 to 130 Hz were about a microradian; hence motion-generated noise must be further reduced by about 80 dB. This noise in the ELF signal can be reduced by adaptively determining a vector approximately equal to the earth's magnetic field vector and combining it vectorially with the SQUID outputs. This adaptive processing has been studied using a computer simulation of the SQUIDs and motion noise. A prototype dewar capable of fitting a towed communication buoy maintained a volume large enough for a triaxial SQUID sensor package at the temperature of boiling liquid helium for 102 days.

CONTENTS

A

DEVELOPMENT OF A SUPERCONDUCTING ELF ANTENNA

INTRODUCTION

The Navy's proposed extremely-low-frequency (ELF) strategic communication system is intended to permit reliable, secure, low-data-rate communications from a single transmitter in the United States to submarines at operational depth and at ranges of several thousand kilometers. The skin depth of radio waves in seawater at ELF is tens of meters; hence radio waves in the band of interest (30 to 130 Hz) experienced little attenuation in penetrating to substantial depths beneath the ocean surface. The required receiver sensitivity in this environment is approximately 200 dB below 1 $V/m\sqrt{\text{Hz}}$ (10^{-14} $T/\sqrt{\text{Hz}}$), a level of performance that can be achieved by currently available E-field trailing-wire antennas.

To minimize operational constraints on submarines attempting to receive ELF messages, it is necessary to provide them an omnidirectional receiving capability. The E-field trailing wire, which is an elementary dipole, has a cosine-shaped azimuthal antenna pattern. It is not practical to design a transverse E-field sensor with adequate sensitivity to complement the trailing wire, which means that a trailing-wire H-field antenna is necessary. However the best demonstrated sensitivity for an H-field antenna trailed at speeds of operational interest is far below the required value. Consequently we are investigating the feasibility of using a superconducting quantum interference device (SQUID) to provide both the required sensitivity and the necessary omnidirectionality. As indicated in previous discussions of this program [1,2], a number of engineering questions must be answered before the feasibility of a SQUID for this application can be determined.

One of the most serious problems relates to noise from rotation of the SQUID sensor in the earth's magnetic field of 5×10^{-5} T. Because the earth's field is uniform on the physical scale of the typical SQUID, a set of orthogonal sensors can be used to sum the vector components continuously and thus permit the earth's field to be removable as a dc component. One difficulty is providing enough dynamic range in the parts of the system ahead of the vector summing stage to prevent the SQUID electronics from being saturated, and another difficulty is achieving orthogonality among the sensors. If completely free rotation of the SQUID in the earth's field is assumed, the total dynamic range requirement is about 196 dB. This figure is far in excess of the available dynamic range of electronic components and, in fact, of SQUIDs themselves; thus a certain degree of motional stability must also be provided. Assuming that electronics can be provided with linear dynamic range approximately equal to that which is available in SQUIDs, a figure of 130 to 140 dB, the rotation of the sensor must be constrained to less than 10^{-3} radian to permit the necessary performance.

These circumstances suggest five major subproblems in demonstrating the feasibility of SQUIDs for underwater reception of ELF communications:

Manuscript submitted March 1, 1976.

- Providing adequate electronic and sensor sensitivity to permit detection of the ELF signal in noise of roughly 10^{-14} $T/\sqrt{\text{Hz}}$;

- Providing 130 to 140 dB linear dynamic range;

- Constraining sensor motion to 10^{-3} radian;

- Providing adequate orthogonality among vector sensors to permit motional noise to be removed by vectorial summation;

- Developing a signal-processing technique to reduce the motional noise to an acceptable level in real time.

In addition to these five subproblems, a sixth matter is the need to demonstrate that a suitable cryogenic environment can be provided for a SQUID, which must be operated in a liquid helium bath, without unacceptable logistical complications, without physical danger to a submarine host vessel, and without unacceptable risk to submarine security.

It is the purpose in this report to describe the results of the research that has been undertaken to investigate these six matters.

MOTION STABILITY MEASUREMENTS

The noise environment of a submarine could possibly permit a SQUID to be boom-mounted from a location on the hull or superstructure. However submarine-generated electromagnetic noise may make it necessary to tow the SQUID in a buoy as much as 100 meters away. In these circumstances the hydrodynamic stability of the buoy will determine the achievable limits on sensor motion, and such a "worst case" was thus chosen for the feasibility testbed.

An experimental buoy (Fig. 1), designed by the David Taylor Naval Ship Research and Development Center to be hydrodynamically stable, was subjected to extensive towing tests in the David Taylor towing basin. The buoy, which is 3.7 meters long and 0.5 meter in diameter, was instrumented with a triaxial rate gyroscope and a triaxial linear accelerometer and was towed in a 650-meter basin at between 2 and 7 knots. Several different body trim angles were investigated at each speed, and runs were repeated several times to insure statistical significance of the data. The top trace in Fig. 2 is a recording of the output from one rate gyroscope as an example. The time integral of this output is shown in Fig. 2 (bottom trace) in order to display the actual motional excursions in milliradians. An oscillation approximately 0.4 milliradian in amplitude with a period of 2 seconds is evident. The larger oscillation with a period of about 20 seconds is an artifact of the signal processing.

The data were also analyzed by a fast-Fourier-transform technique to display the spectral composition of the noise, and examples of these noise spectra are shown in Fig. 3 for towing speeds of 4 and 7 knots. The data show low-frequency motions of the body that increase in bandwidth as speed is increased. The 4-knot spectrum occupies a band

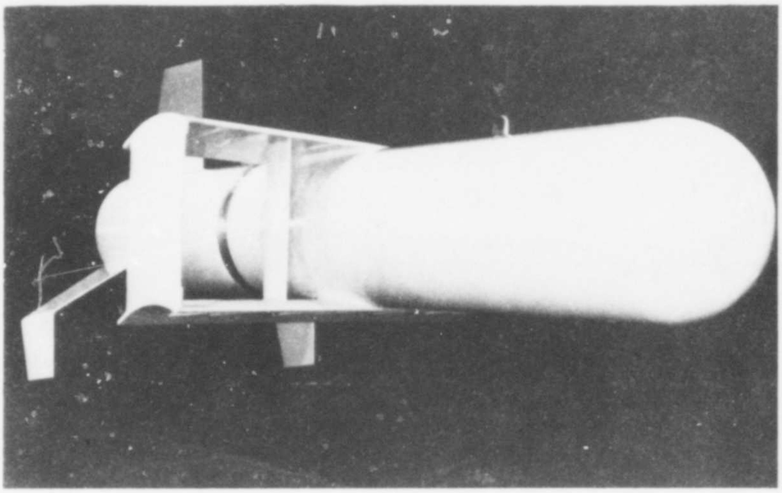

Fig. 1 — Towed communication buoy used for the motion spectrum measurements

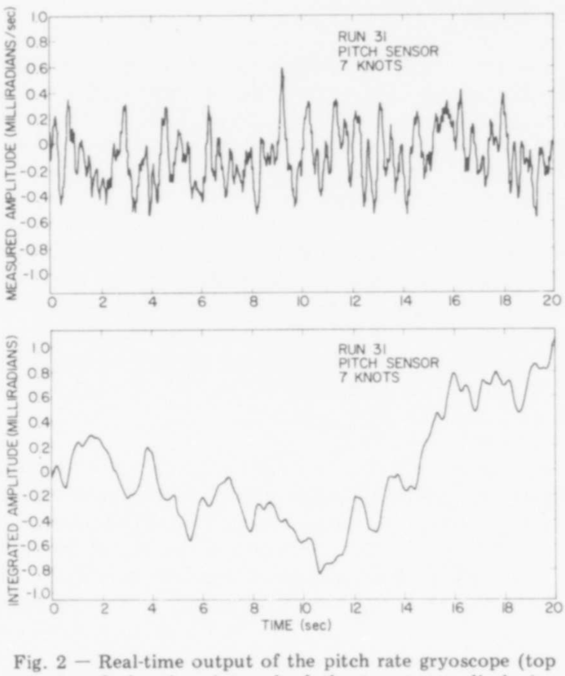

Fig. 2 — Real-time output of the pitch rate gryoscope (top trace) and the time integral of the top trace, displaying pitch angular excursion as a function of time (bottom trace)

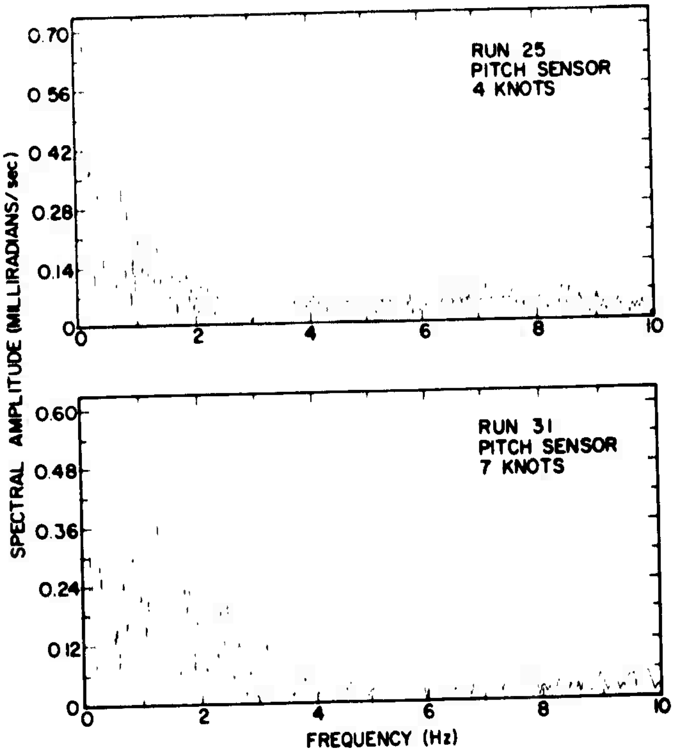

Fig. 3 — Spectra of the pitch-rate gyroscope output for two towing speeds

of about 0 to 2 Hz, and the 7-knot bandwidth extends from 0 to 4 Hz. There is no evidence of any substantial increase in the amplitude of these motions with increasing tow speed. The maximum amplitude in the data is about 7×10^{-4} radian/second. Figure 4 is the integration of the data in Fig. 3 and therefore represents motional excursions of the buoy in the 0 to 10 Hz band. These integrated data show the buoy excursions to be below 10^{-3} radian in the 0 to 10 Hz band.

Typical accelerometer data, which provide information at higher frequencies, are shown in Fig. 5. The data are expressed in radians/s^2 (angular acceleration) relative to 10^{-3} radian/s^2. The spectral peaks at 35 and 42 Hz are due to vortex shedding from blunt trailing edges of the buoy hydrofoils and could be reduced by proper streamlining. The peak at 60 Hz is due to power frequency contamination. Integration of these data indicates that motional excursions within the 30 to 130 Hz ELF bandwidth can be constrained to less than 10^{-6} radian.

To summarize the motion stability measurements, the low-frequency excursions, which are 10^{-3} radian at most, are the largest in amplitude and hence establish the necessary dynamic range. This degree of motion requires a dynamic range of 136 dB and is within the established goal of 130 to 140 dB. The in-band motion of 10^{-6} radian generates a signal of 5×10^{-11} T, which is 76 dB above the receiver sensitivity. The signal-processing technique that will be discussed is capable of reducing the in-band motion noise by at least this amount.

Further details on the motion-spectrum tests can be found in Ref. 3.

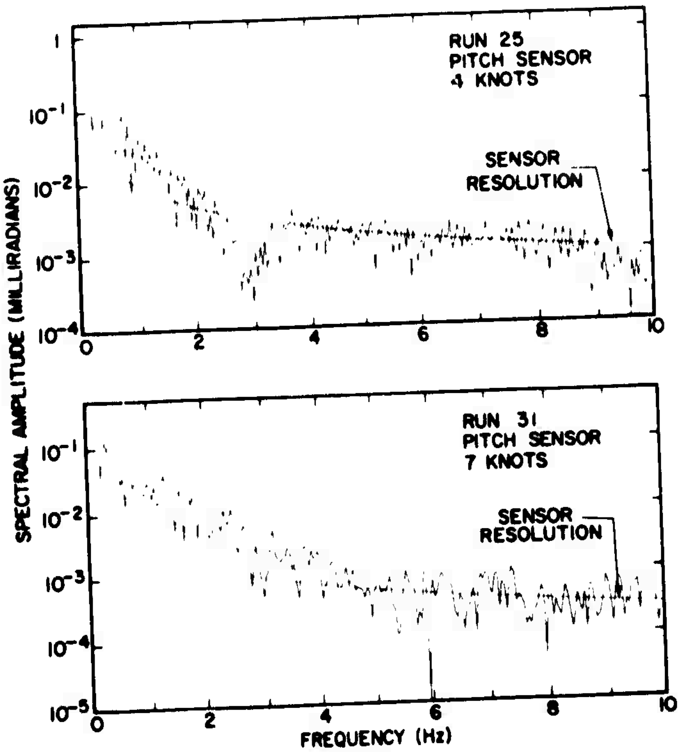

Fig. 4 — Integrals of the spectra shown in Fig. 3, displaying pitch angular excursion on a logarithmic scale as a function of frequency. In each case the sensor resolution curve displays the computed sensor noise level.

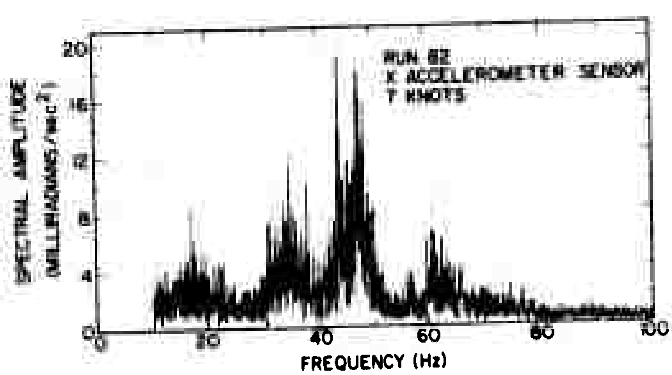

Fig. 5 — Spectrum of the x-oriented accelerometer output. The spectrum noise floor can be observed between 80 and 100 Hz.

CRYOGENIC ENVIRONMENT

Present technology can solve the engineering problems of storing, handling, and cycling liquid helium through a refrigerator with relative ease, even in a shipboard environment. If the helium-handling systems are designed with care, this inert gas poses no significant personnel safety hazard. For an application in which low-noise receiving sensors must be operated in a cryogenic environment, however, it is important that pumps and electric motors, with moving parts made of ferrous metals or conducting bodies that may allow eddy current flow, be kept as far from the sensors as possible. It was decided that the

simplest and most reliable method of providing the required cryogenic environment, for a SQUID that may have to be towed in a buoy 100 meters from its host vessel, would be to equip the buoy with a container that can carry enough liquid helium to keep the sensor cool for a typical maximum submarine deployment period of about 90 days. Some of the considerations that contributed to this decision are described in Ref. 4.

Accordingly an investigation was made of the feasibility of storing in a container small enough to fit into a typical communication buoy enough liquid helium to provide 90 days cooling for a SQUID system of appropriate dimensions to satisfy the ELF communication requirement discussed. This investigation required the design of a horizontal, superinsulated dewar container with a 180-liter liquid-helium capacity. Figure 6 is a drawing of the dewar that was designed by Superconducting Technology, Inc., to meet these requirements. It is a right circular cylinder 1.8 meters long and 0.56 meter in diameter and will fit into an AN/BRA-8 communication buoy. Figure 7 is a photograph of the dewar that was procured to test the dewar design. This dewar successfully maintained a SQUID at liquid helium temperatures for 102 days and thus demonstrated the feasibility of providing the necessary cryogenic environment. The dewar performance is further discussed in Ref. 5.

SENSITIVITY, DYNAMIC RANGE, AND ORTHOGONALITY

Requirements on sensitivity and linear dynamic range have been described. Physical orthogonality of the sensor elements is also related to an adaptive process that will be described for the removal of noise from motion of the triaxial SQUID sensor in the earth's magnetic field. In particular, if the sensors can be made orthogonal to an adequate degree, then certain error terms in the adaptive signal processing will be small and will greatly simplify the computations that must be made in the adaptive process.

A triaxial SQUID sensor was procured for test purposes with the specifications listed in Table 1. The device was designed and manufactured by SHE, Inc., and employed shielded point-contact-type SQUIDs that were coupled to pickup loops wrapped on a precisely machined quartz block about 7 cm on a side. Figure 8 is a photograph of the pickup assembly and shielded SQUIDs. The grooves in the quartz block accommodate both the triaxial pickup loops and a calibration coil. Leads from this assembly are coupled through the fiberglass mounting to the SQUIDs, which are in a doughnut-shaped superconducting shield immediately behind the mounting. Figure 9 is a photograph of the pickup loop assembly and shielded SQUIDs with a protective can in place, showing the mounting boom, baffles, and radiofrequency circuitry. This entire assembly is placed into a liquid helium bath, with the SQUIDs and pickup coils at the bottom. The three SQUID axes have independent cables to control circuits that can be placed as far as 100 meters from the dewar.

The triaxial test SQUID has been tested in the noise environment of the surface atmosphere, which is approximately 40 dB noisier than its design environment, with an electromagnetic shield made of superconducting lead around it to permit its sensitivity to be checked at lower noise level, and also on the ocean floor at a depth of 100 meters. Figure 10 is a comparison of ELF transmitted signals from the Navy test transmitter in

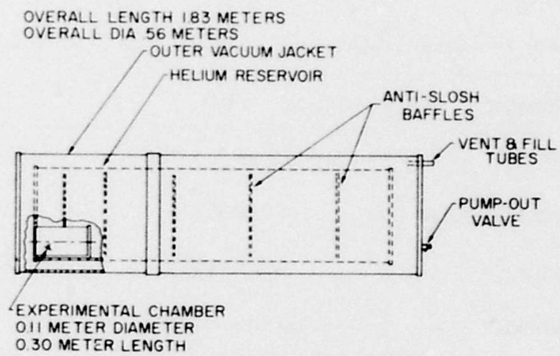

Fig. 6 — Long-hold-time dewar designed to fit a communication buoy

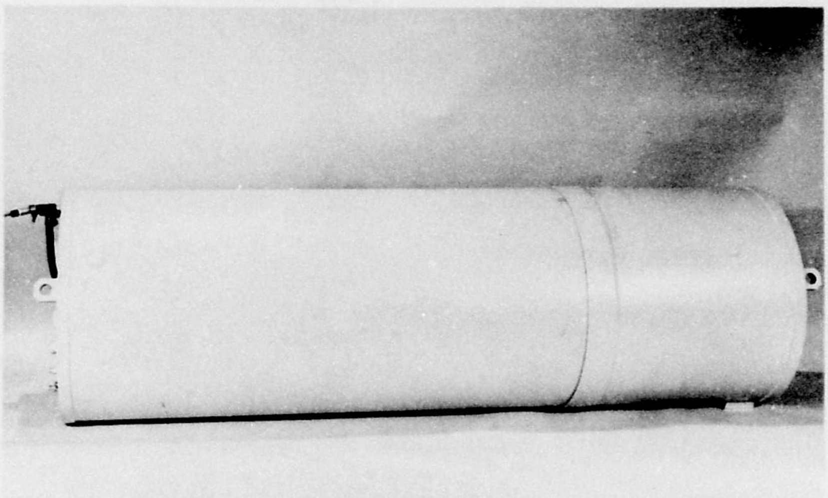

Fig. 7 — Long-hold-time dewar having the design shown in Fig. 6 and used to test the feasibility of storing enough liquid helium to cool a SQUID for 90 days

Table 1 — Specifications of the SQUID ELF-Antenna Test Device

Parameter	Goal	Achieved
Sensitivity	-200 dB re 1 $V/m\sqrt{\text{Hz}}$	-198 dB re 1 $V/m\sqrt{\text{Hz}}$
Linear dynamic range	140 dB	139.2 dB
Orthogonality	10^{-4} radian	0.7×10^{-4} radian
3-dB bandwidth	30 to 130 Hz	0 to 130 Hz

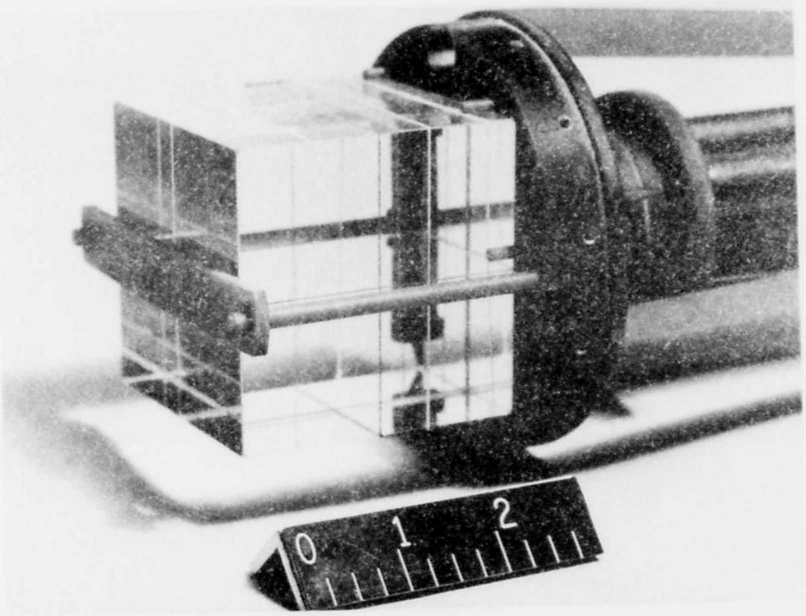

Fig. 8 — Flux transformer assembly of the SQUID antenna. (The scale is in inches.)

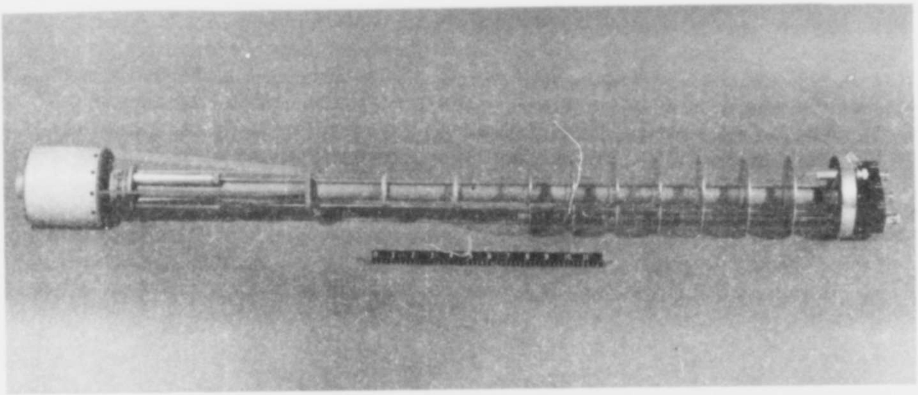

Fig. 9 — Photograph of the SQUID antenna probe. The flux transformer assembly shown in Fig. 8 is hidden by the protective fiberglass shield on the left-hand side of the probe. (The scale is in inches.)

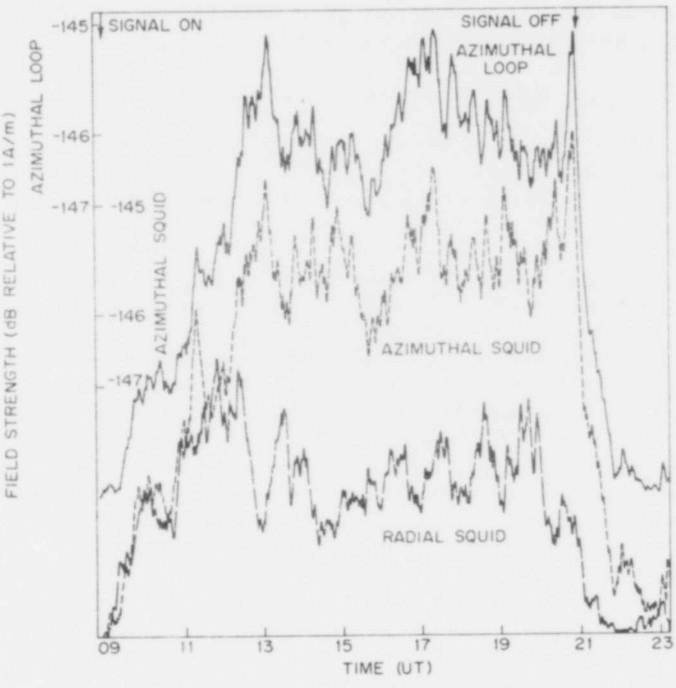

Fig. 10 — Comparison of transmitted ELF signals received on the SQUID antenna and on a conventional air-core loop antenna. The azimuthal loop and azimuthal SQUID traces are offset vertically for display purposes.

Wisconsin as received on the triaxial SQUID and on a conventional air-core loop antenna. Two of the three SQUID axes appear and are shown independently, because in this stationary test no motion-noise processing was necessary. The azimuthal signal is the main component of the transmitted energy, but at receiving locations near the transmitter a radial component also exists. This radial component is shown for illustrative purposes on one SQUID axis in Fig. 10 but is unscaled. It is apparent that the signal-to-noise ratios of the loop and SQUID azimuthal channels are similar (the SQUID and loop channels are offset on the figure to permit convenient comparison -- their actual signal levels are the same), and that the temporal behavior of the signals received on them is qualitatively similar. Slight differences in frequency response and signal processing between the two systems are responsible for the small differences in the appearance of the two signals.

SIGNAL PROCESSING FOR MOTION-NOISE REDUCTION

The towing tests described earlier indicate that buoy motion in the 30 to 130 Hz band can be constrained to be less than 10^{-6} radian. However additional motion compensation must be employed to reduce the level of motion-induced noise still further. The signal induced in a magnetic-vector sensor rotated through an angle Ω in an earth's magnetic field $\mathbf{H}_e$ from an initial orientation θ_0 of the sensor axis relative to $\mathbf{H}_e$ is

$$H_m = H_e[\cos\theta_0 (\cos\Omega - 1) + \sin\theta_0 \sin\Omega]. \tag{1}$$

For $H_e = 5 \times 10^{-5}$ T and $\Omega = 10^{-6}$ radian, in a 1-Hz bandwidth the resulting H_m is 76 dB above the sensitivity requirement of 10^{-14} $T/\sqrt{\mathrm{Hz}}$. In this section an adaptive signal-processing technique will be discussed which can provide *at least* this remaining degree of motion compensation.

An adaptive technique is required because the output of a SQUID sensor is independent of the absolute value of the magnetic field along the sensor axis. That is, the SQUID sensor follows external magnetic field changes accurately, with a low noise level and true dc response, but the actual magnetic field value along the axis of the sensor is never known. However this magnetic field value must be determined to remove motion noise. The essence of the technique used to serve this purpose is that by sampling the *changes* in magnetic field that occur as the SQUID sensors undergo motion in the earth's field, and knowing the functional form which these changes must assume, then the absolute values of the magnetic field components can be determined by the parameter estimation methods that have been developed for adaptive control. The adaptation technique that has been developed for this purpose is described more fully in Ref. 6 and will be summarized here.

For sensors that are perfectly orthogonal a combination of the three sensor outputs may be formed that is independent of sensor orientation. This combination is simply a vector sum. If $\mathbf{H}_m$ is defined as the sensor output due to motion in the earth's dc field $\mathbf{H}_e$, the quantity $|\mathbf{H}_e + \mathbf{H}_m|^2$ is invariant and equal to H_e^2, because in the absence of signal and noise there is no other source of magnetic field strength than $\mathbf{H}_e$. Thus

$$|\mathbf{H}_e + \mathbf{H}_m|^2 = 2\mathbf{H}_e \cdot \mathbf{H}_m + \mathbf{H}_m^2 + \mathbf{H}_e^2 = \mathbf{H}_e^2 \tag{2}$$

or

$$2\mathbf{H}_e \cdot \mathbf{H}_m + \mathbf{H}_m^2 = 0. \tag{3}$$

In addition to an output generated by motion in the uniform field of the earth, the SQUIDs also respond to the ELF signal vector $\mathbf{H}_s$, so that the total sensor output is

$$\mathbf{H}_0 = \mathbf{H}_m + \mathbf{H}_s . \tag{4}$$

Computing $2\mathbf{H}_e \cdot \mathbf{H}_0 + \mathbf{H}_0^2$ and making use of Eq. (3) gives

$$2\mathbf{H}_e \cdot \mathbf{H}_0 + \mathbf{H}_0^2 = 2\mathbf{H}_e \cdot \mathbf{H}_s + 2\mathbf{H}_m \cdot \mathbf{H}_s + \mathbf{H}_s^2 . \tag{5}$$

The ELF signal amplitude $|\mathbf{H}_s|$ is 10^{-14} T, as a lower limit, and the maximum in-band value of $|\mathbf{H}_m|$ is 10^{-10} T. Substitution of these values into Eq. (5) indicates that the second and third terms on the right-hand side are nearly six orders of magnitude lower than the first term. Hence there remains an error quantity S defined as

$$S = 2\mathbf{H}_e \cdot \mathbf{H}_0 + \mathbf{H}_0^2 = 2\mathbf{H}_e \cdot \mathbf{H}_s . \tag{6}$$

The quantity S is proportional to the signal vector and, when properly evaluated, is independent of sensor orientation.

The inclusion of the effects of sensor nonorthogonality, sensitivity differences, and offset errors does not affect the form of the equation for S. The values of the components of $\mathbf{H}_e$ are modified by these deviations from the ideal case; these modified components of $\mathbf{H}_e$ are relabeled and become the components A_1, A_2, and A_3 of a vector $\mathbf{A}$, called the adaptive vector, that is only approximately equal to $\mathbf{H}_e$. The equation for S takes the form

$$S = 2\mathbf{A} \cdot \mathbf{H}_0 + \mathbf{H}_0^2 . \tag{7}$$

When $\mathbf{H}_s$ is removed by filtering, the error quantity S as given by Eq. (6) is zero. In the adaptive process represented by Eq. (7) this circumstance occurs when the proper value of $\mathbf{A}$ is used.

The adaptive processing then proceeds as follows: the SQUID outputs are low-pass filtered to remove $\mathbf{H}_s$, and the value of $\mathbf{A}$ is found which minimizes S. The value of $\mathbf{A}$ found in this manner is then combined with the *unfiltered* SQUID outputs to give an output proportional to $\mathbf{H}_s$. This final output is free of motion-related noise.

An error analysis shows that for the processing to reduce motion noise by 76 dB, the deviations of the sensor axes from orthogonality in radians and the fractional sensitivity errors of the SQUID outputs must each be less than the quantity $2 \times 10^{-10}/\Omega^2$, where as before Ω is the peak platform motion in radians. If $\Omega = 10^{-3}$ radian, as measured in the motion stability tests described, then this quantity has the value 2×10^{-4}. Table 1 shows that the deviations of the sensor axes from orthogonality are less than 0.7×10^{-4} radian; and the fractional sensitivity errors of the SQUID putputs are less than 10^{-6}.

The principal task of the adaptive processing is to determine the values of the components of **A** rapidly and accurately. Two techniques have been investigated to determine the adaptive vector **A**. The first is a least-squares technique that determines **A** by minimizing the integrated value of S^2 over a time interval T_0. The second is a continuous steepest descent method that updates the current value of **A** according to the integrated value of S.

These two adaptive techniques have been investigated using a computer simulation (Fig. 11) of the SQUID sensors and the adaptation. The input signals, labeled θ_i in Fig. 11, are the tape-recorded outputs of the three rate gyroscopes that were mounted on the buoy during the motion stability measurements described earlier. The outputs of the rate gyros are the angular time rates of change of the buoy orientation in three orthogonal directions. Integration of the rate gyro signals gives the angular excursions of the buoy. By combining the buoy excursions with assumed values of the components of the earth's magnetic field in an Euler transformation matrix, magnetic field signals are generated that simulate the motion-induced magnetic field variations that would have been observed if SQUID sensors had been mounted in the buoy. The effects of nonorthogonal sensors are included by a transformation from an orthogonal to a nonorthogonal coordinate system whose deviations from orthogonality are specified by the angles Ω_{ij}. These procedures yielded the inputs to a computer simulation of the least squares fit and the steepest descent processing scheme. The output of the adaptive processing S was Fourier analyzed by a standard fast-Fourier-transform (FFT) program. The simulated SQUID outputs were also Fourier analyzed for comparison with the Fourier transform of S.

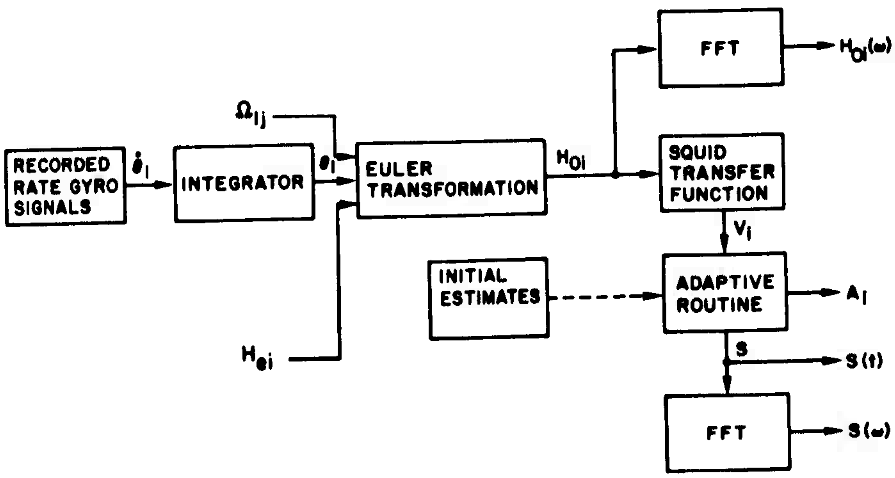

Fig. 11 — Computer simulation of the adaptive processing. The initial estimates are required only for the steepest descent technique.

The main emphasis of the computer simulation was to establish that the least squares and steepest descent processing techniques could indeed provide sufficiently accurate estimates of the error quantities. The frequency response of the rate gyros was limited to about 20 Hz, so that a detailed investigation of the noise in the output S in the 30 to 130 Hz ELF band was not possible. For the purposes of the simulation the information below 20 Hz is sufficient, because the large-amplitude-motion excursions that occur below 5 Hz provide the information by which the adaptive technique can determine the error quantities and thereby remove motion noise above 30 Hz.

The results of the processing using the data from one typical towing test run will be presented. The speed was 7 knots and the run duration approximately 90 seconds, although only approximately 30 seconds of the run could be processed at one time because of computer limitations.

Least Squares Adaptation

The top trace in Fig. 12 (trace A) displays a SQUID output (V_1) as an example of the inputs to the least squares adaptive routine. The values of the earth's field components H_{ei} were held constant during the duration of Fig. 12. The nonorthogonality angles were set equal to zero. Plots B and C in Fig. 12 show the variation of the estimates of one error quantity (A_1) as given by the least squares routine. In plot B each estimate of A_1 uses the previous 2 seconds of data. Since the points are spaced by only 1 second, the data blocks used to compute A_1 overlap by 50 percent. In plot C each estimate of A_1 uses the previous 15 seconds of data, with an overlap of 90 percent from one data block to the next. Clearly the longer span of data provides a better estimate of A_1. Similar results are obtained for the other error quantities. The optimum value of adaptation time T_0 is approximately 10 seconds for the input data used in this simulation; a longer length of time gives only a small improvement in the error quantities. This value of T_0 is of course optimum only for the simulation. In an actual SQUID receiver, longer or shorter values of T_0 may be optimum. The least squares technique is capable of estimating the components A_i with the necessary accuracy. Trace D in Fig. 12 is a plot of S with $T_0 = 15$ seconds. Figure 13 compares the spectrum of V_1 with the spectrum of S. The spectrum amplitude above 10 Hz is seen to be about a factor of 25 below the maximum allowable value of $2\mathbf{H}_e \cdot \mathbf{H}_s$, which is $10^{-18}\ T^2$.

Steepest Descent Adaptation

The steepest descent adaptation technique also was investigated. It was found that the integration time T_0 could vary over a large range without materially affecting S, but an investigation of the convergence of the adaptive constants to their exact values and hence S to zero revealed that unless the initial values were close to the exact values, convergence could not always be insured. Possibly the time limit of 30 seconds imposed by the memory size of the computer is not sufficiently long to permit convergence to be obtained. The spectrum of S, as determined by the steepest descent technique, was similar in amplitude and other features to the spectrum of S computed from the least squares technique. The behavior of the spectrum amplitude as a function of the nonorthogonality angles was also similar.

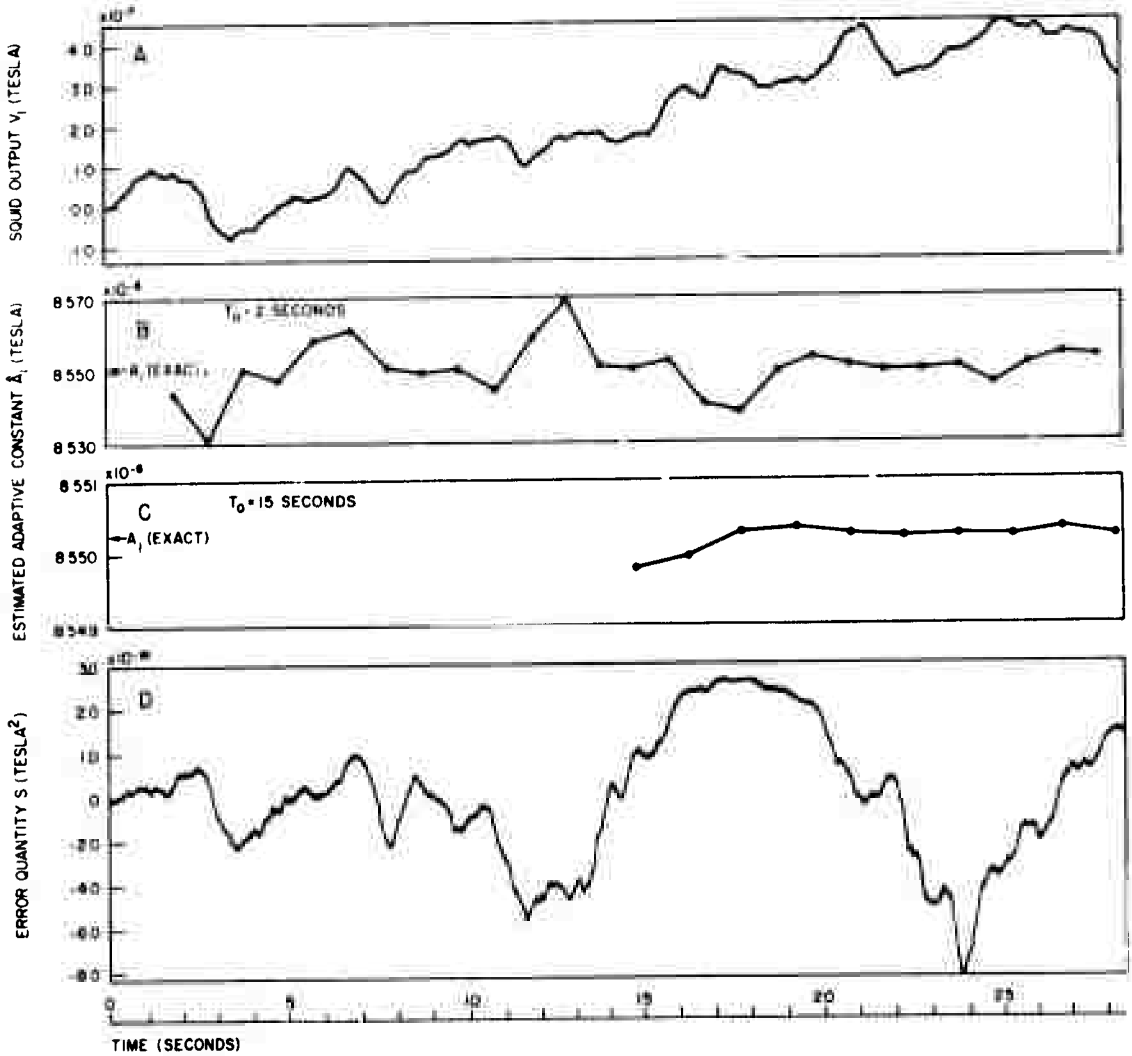

Fig. 12 — Computer simulation results for the least squares technique. Trace A is the time variation of the SQUID output V_I. Traces B and C display the time variation of the estimated values of A_1 for a value of T_0 of 2 and 15 seconds respectively. The exact value of A_1 is also shown on the left-hand scale in both traces. Trace D is the time variation of the error quantity $\bar{S}$.

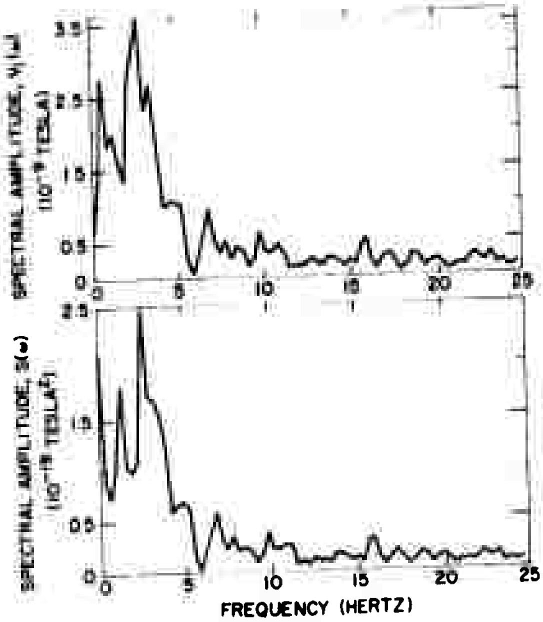

Fig. 13 — Frequency spectrum (top) of the SQUID output V_1, given by trace A in Fig. 12, and frequency spectrum (bottom) of the error quantity S, given by trace D in Fig. 12.

The simulation demonstrates that the least squares technique is able to provide accurate estimates of the adaptive constants without the need for any initial estimates. However the method is not a closed-loop technique and requires up to 10 seconds of data to evaluate the adaptive constants, which is a decided handicap. The requirement of a digital microprocessor might be considered a disadvantage in some applications, but in the submarine communication system under consideration here a microprocessor can probably be provided. The essentially continuous determination of the adaptive constants offered by the steepest descent technique and its closed-loop nature make the technique appealing. In applications where a microprocessor or digital computer is not available the steepest descent technique is clearly superior, because it can be implemented by purely analog computing machinery. On the other hand the requirement of an initial value of each of the adaptive constants, which must apparently be rather close to the true value, is a disadvantage.

An optimum system might consist of a hybrid combination of the two techniques. Processing could be initiated by zeroing the SQUID outputs, entering 10 seconds of SQUID output into a computer memory, and solving for the adaptive constants using the least squares technique. This value would then be used to begin the integration of the steepest descent equations, which could be by analog or digital techniques. Continuous monitoring of the output S by a threshold detector would allow verification of the tracking of changes in the earth's field. If the noise in S became excessive, the SQUID outputs could be rezeroed and the determination begun anew.

CONCLUSIONS, FUTURE PLANS, AND RECOMMENDATIONS

It has been shown that the cryogenic environment necessary for SQUID use in a submerged receiving application can be provided simply and reliably by suitable packaging of a liquid-helium dewar. A horizontal dewar, of an appropriate size to fit in a typical communication buoy, has been procured and tested and has demonstrated a 102-day hold time.

Motion-stability measurements have been made on a hydrodynamically stabilized buoy in a towing channel at the David Taylor Naval Ship Research and Development Center and have shown that motion in the 0 to 30 Hz band can be constrained to 10^{-3} radian. Motion within the 30 to 130 Hz ELF reception band was held to less than 10^{-6} radian.

In view of these estimated buoy performance limits, a triaxial test SQUID was procured with a 139-dB linear dynamic range, a value that will permit the SQUID to be used aboard a towed buoy without electronic saturation due to motion of the SQUID in the earth's magnetic field. The SQUID also was configured with a triaxial pickup assembly in which the three pickup loops were orthogonal to within 0.7×10^{-4} radian. This high degree of orthogonality simplifies the adaptive signal processing scheme that is necessary to employ a SQUID in this application.

Because a SQUID cannot sense the absolute value of the earth's magnetic field, the earth's field strength must be determined adaptively to a degree of precision that will permit it to be removed from the vector sum of the sensor outputs to below noise level. Two adaptive techniques were studied and evaluated with the aid of simulated motion data from the motion stability measurements. A hybrid of open-loop (least squares) and closed-loop (steepest descent) adaptation methods was found to be the most attractive approach to solving the signal-processing problem.

The principal remaining effort in this exploratory development program will be devoted to the following matters.

- Perform off-line adaptive processing tests to evaluate adaptive methods using a PDP 11/40 minicomputer;
- Procure high-speed analog/digital electronics to interface the SQUID directly to the computer. Perform further adaptive processing tests.
- Measure the ELF noise spectrum of a submarine in the San Clemente test range;
- Tow a SQUID system in a buoy and record the ELF signal from the Navy test transmitter. Evaluate the adaptive signal processing (off line).

These investigations will permit the feasibility of actual SQUID operation in the underwater environment to be demonstrated. They will also permit on-line adaptation to be demonstrated *in principle*. However engineering of an entire communication receiver and signal processor for operation in an underwater environment will not be undertaken. Furthermore, the adaptive processing method will not be refined to the point at which true,

real-time adaptation will be possible. Both of these matters are left until a further investigation of the underwater ELF noise environment is completed. Some preliminary observations of submarine-emitted ELF noise will be conducted as the opportunity arises during underwater tests of the SQUID and electronics. These observations are intended only to lend advance insight into the magnitude of the submarine noise survey that should be conducted and to give an initial indication of whether boom or buoy mounting is more attractive.

The following items are recommended for the advanced development program:

- Submarine noise survey,
- Boom-mount development,
- Towed buoy development,
- Real-time signal processor development, and
- Field verification.

The boom-mount and buoy-development programs should be pursued in parallel until a clear preference is expressed by results of the noise survey and signal processing development programs. The advanced development program should take 2 years and should cost approximately $1 million, exclusive of field-test scheduling delays and field platform installation costs.

ACKNOWLEDGMENT

We gratefully acknowledge the benefit of expertise in cryogenics and superconductivity provided us by Martin Nisenoff and Stuart Wolf, both of this laboratory, in assessing the applicability of SQUIDs to the ELF receiving function, in specifying and evaluating the test devices, and in assisting us with our field tests.

REFERENCES

1. S.A. Wolf, J.R. Davis, and M. Nisenoff, "Superconducting Extremely Low Frequency (ELF) Magnetic Field Sensors for Submarine Communications," IEEE Trans. Comm. COM-22, 549-554 (1974).
2. S.A. Wolf, M. Nisenoff, and J.R. Davis, "Superconducting ELF Magnetic Field Sensors for Submarine Communications," NRL Report 7720, May 1974.
3. R.J. Dinger and J. Goldstein, "Motion Stability Measurements of a Submarine-Towed ELF Receiving Platform," NRL Report 7974, Dec. 1975.
4. J.E. Cox, "Potential Cooling Methods for an ELF Squid," NRL Memorandum Report 2899, Oct. 1974.

5. R.J. Dinger, J.R. Davis, and M. Nisenoff, "Long-Hold-Time Liquid-Helium Dewar For Cooling of a SQUID ELF Antenna," NRL Memorandum Report 3256, March 1976.

6. R.J. Dinger and J.R. Davis, "Adaptive Methods for Motion-Noise Compensation in Extremely Low Frequency Submarine Receiving Antennas," submitted